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## The Off-nuclear Starbursts In NGC 4038/4039 (The Antennae Galaxies)

Z. Wang<sup>1,4</sup>, G. G. Fazio<sup>1</sup>, M. L. N. Ashby<sup>1</sup>, J. -S. Huang<sup>1</sup>, M. A. Pahre<sup>1</sup>, H. A. Smith<sup>1</sup>, S. P. Willner<sup>1</sup>, W. J. Forrest<sup>2</sup>, J. L. Pipher<sup>2</sup> and J. A. Surace<sup>3</sup>

### ABSTRACT

Imaging of the Antennae galaxies (NGC 4038/4039) with the Infrared Array Camera (IRAC) aboard the Spitzer Space Telescope reveals large concentrations of star forming activity away from both nuclei of the two merging galaxies. These images confirm earlier findings based on ISO data with lower angular resolution. The short wavelength emission shows numerous compact sources identified as stellar clusters. At the longer wavelengths, bright, more amorphous and filamentary features correlate well with the known distributions of denser gas, warm dust, and HII regions. There are also fainter, more diffuse components at all wavelengths that permeate the entire region and extend into the two tidal tails. Non-stellar dust emission dominates the 5.8 and 8.0 $\mu$ m images, accounting for as much as 79% of the light at 5.8 $\mu$ m and 95% at 8 $\mu$ m, averaged over the entire galaxy. Assuming that the non-stellar emission traces star formation, the IRAC data provide a view into the total underlying star forming activities unaffected by obscuration. Using the flux ratio of non-stellar to stellar emission as a guide, we map the local star formation rate in the Antennae and compare that to similar measurements in both normal and infrared-luminous galaxies. This rate in the active regions is found to be as high as those seen in starburst and some ultra-luminous infrared galaxies on “per unit mass” basis. The two galactic centers actually have lower star forming rates than the off-nuclear regions despite the presence of abundant dense gas and dust, suggesting that the latter is a necessary but not sufficient condition for on-going star formation.

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<sup>1</sup>Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138-1516

<sup>2</sup>Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627-0171

<sup>3</sup>Spitzer Science Center, Caltech, Pasadena, CA 91125

<sup>4</sup>email: zwang@cfa.harvard.edu

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## 1. Introduction

At an approximate distance of 21 Mpc<sup>1</sup>, the Antennae galaxies provide a vivid illustration of a merging pair of spiral disks carrying a large amount of gas and dust (Toomre & Toomre 1972; Hibbard et al. 2001). Attention to this system has increased over the last ten years since the debut of the Hubble images and the subsequent analysis that revealed thousands of young star clusters possibly being formed as part of the merging process (Whitmore & Schweizer 1995; Whitmore et al. 1999). Theoretical models (Mihos et al. 1993, Mihos & Hernquist 1996; Barnes 2002) have shown that the overall morphology, with its long-stretched tidal tails, can be accounted for via numerical simulations and that the behavior of gas and dust components are a consequence of the gravitational interaction.

Infrared observations from space have opened an important line of inquiry on mergers, beginning with the IRAS All-sky Survey’s discovery linking the “ultra-luminous” infrared galaxies (ULIRGs) with apparent interaction/merger morphology (Sanders and Mirabel 1996). Although not counted as an ULIRG by its absolute luminosity, the Antennae system is nevertheless a typical case study involving both galaxy merger and active star formation. Of special interest are the Infrared Space Observatory (ISO) observations of NGC 4038/4039 that show a significant fraction of the mid-infrared emission may actually come from the “overlap region” that lies between the two nuclei (Vigroux et al. 1996; Mirabel et al. 1998). Several recent analyses have attempted to compare the multi-wavelength datasets of this galaxy pair in order to understand the detailed correlation of various components (Xu et al. 2000; Zhang et al. 2001; Zezas et al. 2002; Kassin et al. 2003). However, the existing mid-infrared data have been limited by the relatively low angular resolution and sensitivity compared to other datasets.

The successful launch and early operations of the Spitzer Space Telescope (Werner et al. 2004) brought greatly enhanced capabilities to mid- and far-infrared observations. As part of the Spitzer Guaranteed Time Observing (GTO) program, we have used the Infrared Array Camera (IRAC, Fazio et al. 2004) to perform broad-band imaging of the Antennae galaxies in four mid-infrared bands covering 3 to 10  $\mu$ m. This paper reports the first results of our observations with IRAC, which provide at least an order of magnitude improvement in sensitivity and a factor of 3 or higher in angular resolution compared to previous instruments.

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<sup>1</sup>In this paper we assume a value of Hubble constant  $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$ .

## 2. Observations and Data Analysis

The Spitzer observations of the Antennae were performed on 24 December 2003. There were a total of 20 individual pointing positions for each of the two IRAC fields-of-view (FOV). At each pointing position, exposures were taken in all four IRAC bands (3.6 and 5.8, or 4.5 and  $8.0\mu\text{m}$ ), with a 5-point Gaussian dithering pattern and 12-second frame time. The area observed with all four IRAC bands exceeds  $20' \times 16'$ , covering the entire extent of the galaxy pair (in V band) including the two long tidal tails, with at least 160 sec total exposure time at every position.

Data analysis was carried out with both the standard SSC science data pipeline and the SAO software package SIP<sup>2</sup>. Standard dark subtraction, linearity correction, and flatfielding were used. After removing instrumental effects and cosmic ray hits, each of the four IRAC bands was flux-calibrated and mosaicked to a single image covering the two galaxies using the “drizzle” method (Fruchter & Hook 2002). Photometry of extended sources was performed on each band by fitting surface brightness isophotes and measuring fluxes with appropriate aperture correction. Astrometry of each data frame was performed based on known positions of 2MASS point sources, with resulting accuracy of better than  $0''.3$ . The FWHMs of point sources in the four bands range between  $1''.4$  and  $1''.6$ .

## 3. The Antennae As Seen in the Four IRAC Bands

The central part of the mosaicked IRAC data covering the main body of the Antennae is shown in the left panels of Figure 1. The bright mid-infrared emission is concentrated in three separate areas: around the two galactic nuclei, the outer “spiral arms” region of NGC 4038, and the “overlap” region (see Figure 2) as previously suggested by the ISO team (Mirabel et al. 1998). In each region, the emission is organized into large irregularly shaped patches of about  $10''$  (1 kpc) in scale, with well-resolved, smaller-scale structures. In addition to these extended emission regions, there are numerous bright unresolved point sources and a diffuse component in all four bands (see contours in Fig. 3a) that permeates the main bodies of the two galaxies and extends to beyond the central region covered by the frames in Fig. 1.

Although the overall morphologies revealed in the four bands show broad similarities, there are clear differences. The two galaxies’ cores appear relatively brighter and more

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<sup>2</sup>SIP (the SAO IRAC Pipeline) was developed by the IRAC Instrument Team at the Smithsonian Astrophysical Observatory.

symmetric in the 3.6 and  $4.5\mu\text{m}$  band. (The center of NGC 4038 is nearly circular, while that of NGC 4039 roughly an oval). On the other hand, the morphology in the  $8\mu\text{m}$  band (and to a lesser extent also at  $5.8\mu\text{m}$ ) appears more filamentary and has amorphous, irregular features (see Fig.2), even though the effective angular resolution differs only slightly. Based on existing spectroscopic data, it is almost certain that emission at these wavelengths arises from the so-called aromatic features (usually attributed to PAHs) at 6.2, 7.7 and  $8.6\mu\text{m}$  (Rigopoulou et al. 1999; Tran et al. 2001). Indeed, IRAC observations of other late-type galaxies (Helou et al. 2004; Pahre et al. 2004; Willner et al. 2004) also found excess dust emission at these wavelengths. The aromatic feature emission is often associated with the warm dust in or near giant HII regions in an ISM-rich environment, and these regions are nearly always sites of active star formation.

The diffuse, extended emission also shows differences among the four IRAC bands. Overall, the longer wavelengths exhibit relatively weaker diffuse emission and fainter tidal tails, further suggesting that the component responsible for the dust emission is more concentrated toward the galaxies' main bodies, where one finds denser gas and more warm dust.

#### 4. Comparison of IRAC Images with Existing Data

The IRAC images can be directly compared with the mid-infrared (7, 9, and  $15\mu\text{m}$ ) data from ISO, ground-based near-infrared (K-band) imaging (Kassin et al. 2003; Brandl 2004; Martini 2004) and spectroscopy (Liang et al. 2001; Mengel et al. 2001), as well as the optical data, including those from the Hubble (Whitmore et al. 1995, 1999). The  $3.6$  and  $4.5\mu\text{m}$  data trace each other well and generally match features seen in the ground-based near-infrared images. This confirms that the emission in the 2 to  $5\mu\text{m}$  range is mainly arising from the underlying, older stellar population with ordinary colors. Both our data and the near-infrared imaging data show that the distribution of the young stellar clusters as seen in the HST images (Whitmore et al. 1999) are far from uniform: they are congregated in groups of size scales of about one to a few kpc. On larger scales they tend to concentrate toward the northern spiral arm, the overlap region, and the two nuclei where one also finds on-going star formation.

IRAC data in the  $5.8$  and  $8.0\mu\text{m}$  bands, on the other hand, are generally more consistent with the longer wavelengths ISO results. More specifically, the new dataset also reveals details not seen by ISO, including asymmetric emission structures near the two galactic nuclei, the filamentary and loop-shaped features in many of the star-forming regions, and the fainter, extended diffuse component that permeates the entire system. The closest correlation, however, turns out to be with the distributions of H $\alpha$  emission and the dust features

seen in absorption in the visible-wavelength image (Figures 2 and 3a). Some of the hollow (or “ring-like”) features have blue stellar clusters in the center (Whitmore et al. 1999), indicative of supernovae or stellar wind-related “superbubble”-type structures in the interstellar medium. Away from the two galactic nuclei, the emission at 5.8 and  $8.0\mu\text{m}$  also shows good correlation with the radio continuum images at 4 and 6 cm (Hummel & van der Hulst 1986; Neff & Ulvestad 2000) and the CO (1-0) map of molecular gas (Stanford et al. 1990; Wilson et al. 2000).

## 5. Off-Nuclei Star Formation as Measured by the Enhanced PAH Emission

Emission features from heated dust are ubiquitous in late-type galaxies and are found to be greatly enhanced in many starburst and ULIRG galaxies. The flux ratio between the dust emission bands and the mid-infrared continuum has been proposed as a quantitative measure of the relative level of starburst activities among infrared luminous galaxies (Genzel et al. 1998; Laurent et al. 1999, 2001; Tran et al. 2001). This approach appears to be broadly successful in categorizing the different types of objects and their power sources. However, one of the complications is that most existing measurements of infrared-luminous galaxies are based on global properties, so it is not clear to what extent they are contaminated by the additional non-thermal power sources such as AGNs. For example, an analysis of 41 ULIRGs finds poor correlation between the PAH feature to continuum flux ratio at  $7.7\mu\text{m}$  and other starburst indicators (Farrah et al. 2003).

The special perspective provided by the Antennae is that the most active star formation is seen in well-resolved regions far away from the galaxies’ nuclei, so the potential “contamination” by an AGN is minimized. Moreover, the two longer-wavelength IRAC bands cover three of the strongest PAH features in this spectral range (at 6.2, 7.7, and  $8.6\mu\text{m}$ ), thus simultaneous observation with all four IRAC bands allows a straightforward comparison of the fluxes with and without the contribution of the PAH bands over the entire galaxy at a high spatial resolution. In order to better assess the contribution of the PAH bands, we define the “non-stellar” (or dust) component of the emission to be the *difference* between the measured flux and a “stellar continuum” flux. The latter was calculated for each of the four bands by normalizing a stellar spectral energy distribution (SED)<sup>3</sup> to an average of IRAC 3.6 and  $4.5\mu\text{m}$  flux at each position. The right panel in Figure 1 illustrates the distribution of the non-stellar emission component.

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<sup>3</sup>At these wavelengths, the results are insensitive to the actual stellar type selected. For convenience we used the Vega A0 V type in the fit.

There is some residual emission at  $4.5\mu\text{m}$ , while the  $3.6\mu\text{m}$  image is slightly negative (over-subtracted, mainly in the overlap region). The residual  $4.5\mu\text{m}$  emission can have several possible origins: either these regions are extremely highly obscured (with  $A_v > 50$ ), such that even at  $3.6\mu\text{m}$ , the selective extinction is still significant; or there could be additional  $4.5\mu\text{m}$  emission sources causing the SEDs to deviate from the stellar template (stars of different stellar types than we assumed, or additional dust emission features). Nevertheless, the overall picture from the right panel of Fig. 1 is that the stellar continuum fit to IRAC 3.6 and  $4.5\mu\text{m}$  data is reasonably good and that most of the emission ( $> 90\%$ ) in these two bands indeed comes from the stellar contribution.

The situation is entirely different for the  $5.8$  and  $8.0\mu\text{m}$  images: most of the emission in these two IRAC bands comes from the non-stellar (i.e., warm dust) component. In fact, over the entire galaxy, the fractional contribution of the non-stellar flux component is  $> 79\%$  for the  $5.8\mu\text{m}$  band and  $> 95\%$  for the  $8\mu\text{m}$  band. Moreover, since the overlap region is not as bright in the continuum as the two galactic cores, this fraction is even higher there. That this non-stellar flux is dominated by the PAH emission is supported by the fact that the average  $[5.8] - [8.0]$  surface brightness ratio for the non-stellar component is consistently about 1.8 mag in all positions. This is very similar to the ratio found in a sample of late-type galaxies based on the IRAC Mid-infrared Hubble Atlas program (Pahre et al. 2004). Theoretical model calculations of dust bands predict a similar factor (Li and Draine 2001). We therefore conclude that the warm dust emission dominates fluxes measured in the 5 to  $8\mu\text{m}$  range virtually everywhere in the main body of the Antennae.

The strong PAH emission in this spectral range is not surprising. Previous data and IRAC observations of other late-type galaxies all suggest such a result, especially for regions of known star formation. However, what stands out in the Antennae is the degree to which the dust emission overwhelms the mid-infrared continuum. The ratio of PAH flux to stellar continuum found in the active regions of this galaxy is much higher (by a factor of at least 4 to 5) than in other late-type galaxies (Pahre et al. 2004) and is comparable to those of many more distant starburst and ULIRG galaxies observed so far with IRAC (Wang et al. 2004). Moreover, unlike the majority of infrared-luminous galaxies, in this case the most intensive PAH fluxes are clearly not coming from the galactic centers but instead from regions far off the two nuclei (i.e., in the outer arms and the overlap region).

Fig. 3b shows the flux ratio of the non-stellar and stellar continuum for IRAC  $8\mu\text{m}$  data. This ratio is similar to but not the same as the “PAH 7.7 (or  $6.2\mu\text{m}$  to continuum” ratio used by several groups (Genzel et al. 1998; Laurent et al. 1999) to measure the starburst contribution of total power output in ULIRGs. (The difference is mainly in accounting for the thermal continuum of warm dust.) If the  $3.6$  to  $4.5\mu\text{m}$  continuum is proportional to the

mass of the underlying stellar population, and the non-stellar dust emission is proportional to the current star formation rate, then this ratio provides an approximate measure of the “star formation rate per unit stellar mass”. Not surprisingly, its value increases dramatically (to 10 – 30) in the overlap region and in the outer spiral arms around NGC 4038. The ratio map in Fig. 3b can be compared with Fig. 3a, in which the IRAC  $8\mu\text{m}$  emission is overlaid (as contours) on the  $\text{H}\alpha$  image (greyscale) of the Antennae. This comparison again suggests that in off-nuclear regions where current star formation is taking place, both the PAH and  $\text{H}\alpha$  emission are bright. (The dust extinction appears to have a lesser effect on the  $\text{H}\alpha$  than broad-band optical images in off-nuclear regions). These are the same regions where ISO found a large increase in mid-infrared continuum at  $15\mu\text{m}$  (Mirabel et al. 1998) and high excitation of ionized gas as measured by the  $[\text{NeIII}]/[\text{NeII}]$  line ratio. In contrast, this non-stellar vs. stellar flux ratio has a much lower value (between 2 and 5) in both nuclei of NGC 4038 and NGC 4039, even though the extinction there is higher.

Despite their prominence in dust emission, the active star forming regions involve only a relatively small amount of stellar mass. Assuming that the integrated luminosity in the shorter-wavelength IRAC bands is proportional to the stellar mass everywhere in the Antennae, the active star forming regions in Fig. 3b (defined as having the flux ratio of (non-stellar)  $8.0\mu\text{m}$  to stellar continuum greater than 7:1) comprise only about 10% of the total stellar mass of the entire system (assuming a constant mass-to-light ratio while accounting for extinction based on the infrared data). The current bolometric luminosity of the Antennae is estimated to be  $4 \times 10^{10} L_\odot$ . But if we assume that a sufficient dense gas exists and that the amount of star formation per unit stellar mass remains as high as in the overlap region after the two galaxies finally merge into one, then the Antennae’s bolometric luminosity could be elevated to at least 10 times greater as a result of the merger, pushing it into the league of ULIRG galaxies such as UGC 5101 or Arp 220. It is at least theoretically possible that such circumstances could occur in the Antennae at a different stage of its merger from the present one.

## 6. Discussion

Several previous works have postulated that the ultimate regulator for the level of star forming activities in a starburst galaxy is the available supply of raw materials, i.e., the amount of cold, dense molecular gas (Efstathiou & Rowan-Robinson 1995; Efstathiou et al. 2000; Gao et al. 2001). Our analysis of IRAC data on the Antennae only partially supports this idea: the areas of star forming activities very roughly coincide with the CO intensity maps (Wilson et al. 2000, 2003) in the off-nuclear regions. However, the amount

of star formation per unit stellar mass is considerably lower in the two galaxies' nuclear regions where, despite the presence of plenty of molecular gas, neither H $\alpha$  nor dust emission is proportionally brighter. In other words, the mere abundance of dense gas is a necessary but may not be a sufficient condition for local starbursts in interacting galaxies. Other factors, such as shocks, are also likely to be important at least in the stages prior to the final coalescence.

Using the flux ratio of mid-infrared dust emission vs. stellar continuum as an indicator of star forming activities may be more appropriate for the Antennae because most of star formation is off-nuclear and thus the effect of AGN is minimal. Our results suggest that the star forming regions in this galaxy are as active as those in the more luminous infrared galaxies, but the activity is localized rather than global. It remains to be addressed whether the nuclear regions of the Antennae have passed their peak star forming epoch or a more active starburst will take place as the merger evolves.

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(Figure 1)

Fig. 1.— Left panel: greyscale plot of the central part of the Antennae in the four IRAC bands: from top to bottom: 3.6, 4.5, 5.8 and  $8.0\mu\text{m}$  bands. Right panel: same as the left, but for the non-stellar emission only. The continuum emission, generated by extrapolating the average of the 3.6 and 4.5  $\mu\text{m}$  images to the appropriate wavelength band, is subtracted. North is up and East is to the left. The angular size of each image is about 4'3 by 3'1 in RA and Dec directions, respectively. The sky background in the  $8\mu\text{m}$  image appear smoother than the other bands because the surface brightness of the emission is much higher.

(Figure 2)

Fig. 2.— (Color Plate 1.) Left: Color-composite image of the central part of the Antennae based on data from the optical (U, V) bands (Kuchinski et al. 2000) and the IRAC  $8\mu\text{m}$  band: Blue: U, Green: V, Red:  $8\mu\text{m}$ . Right: the HST UBV and H $\alpha$  color composite for comparison. The two insets on the upper right show expanded views of a star forming region in the northern spiral arms region. The HST data were taken with the WFPC camera and adapted from Whitmore et al. (1999). The orientation in this figure is indicated by the arrow in the right panel and is different from Fig. 1 and Fig. 3.

(Figure 3)

Fig. 3.— (Color Plate 2.) [a] (left): The IRAC  $8\mu\text{m}$  emission (as contours) overlaid on the  $\text{H}\alpha$  image of the same region (as grey scales). The  $\text{H}\alpha$  image is from the WFPC camera of the Hubble Space Telescope (Whitmore et al. 1999). The contours are from 5 to 120 in steps of 10, in the IRAC flux unit of  $\text{MJy/sr}$ . The outer contour shows the extended diffuse component at  $8\mu\text{m}$ . [b] (right): Ratio of the  $8.0\mu\text{m}$  non-stellar flux to  $4.5\mu\text{m}$  stellar continuum, shown in both greyscale and contours. The contour levels are from 10 to 35, in steps of 5.

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